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SF04

Cloud Fragmentation & the Missing Baryon Problem

Collaborator

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  astro-ph/0406632

Where Are The Baryons?

- Standard Cooling
- Problem: The Characteristic Galaxy Mass
- The Milky Way - Trouble at Home

A New Approach

- Multi-phase Cooling
- Cloud Fragmentation

Why You Should Believe

- High-Velocity Clouds
- Mass of the Milky Way
- Origin of L_*

Where are the Baryons?

- Only ~8% of BBN/LCDM baryons are in stars or cooled galactic gas (Fukugita, Hogan, & Peebles 98; Bell et al. 04)

- Take for example our own Milky Way:

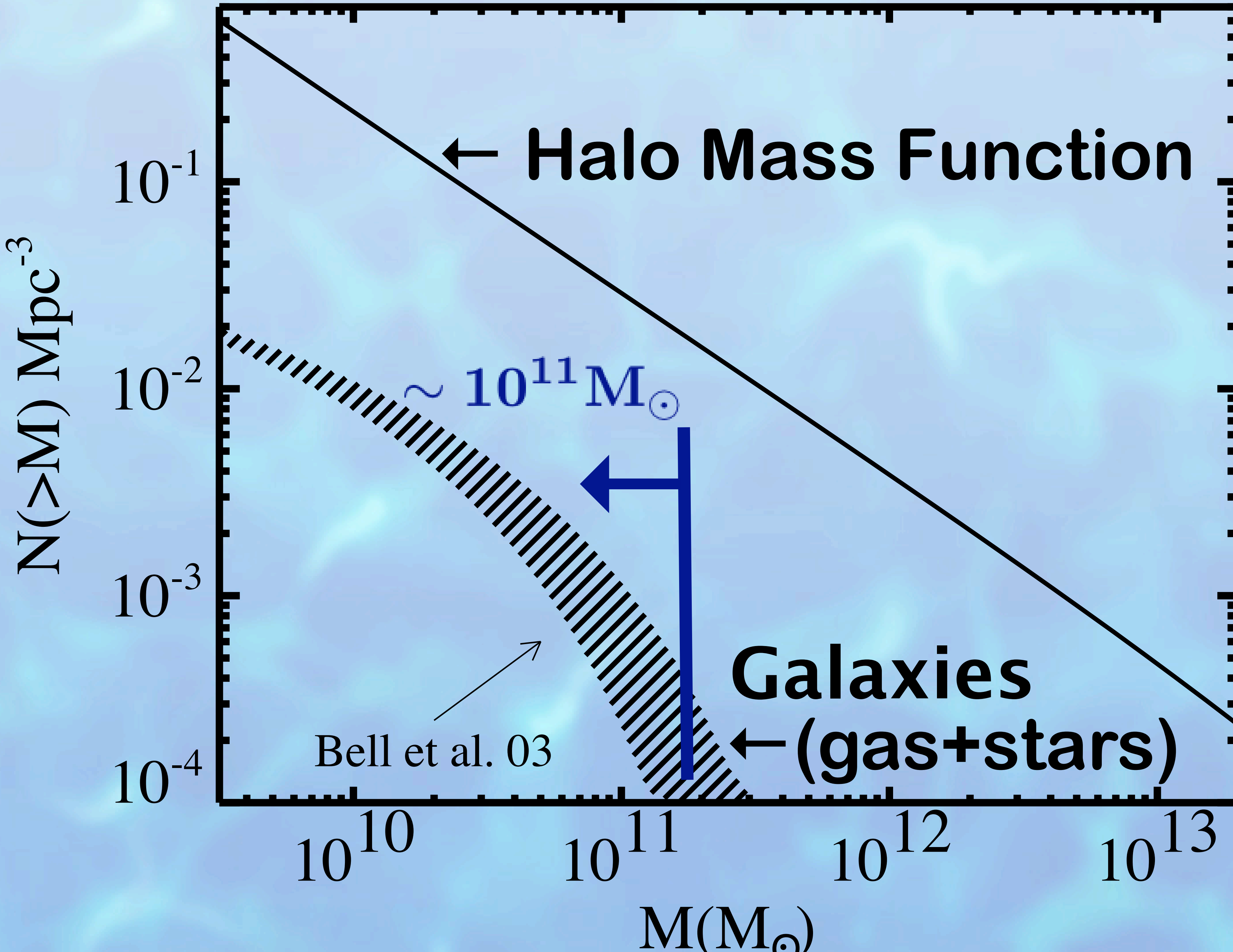
Observe ⇒ $$\mathrm{M_G} = (4-6) \times 10^{10} \mathrm{M}_\odot$$ (Dehnen & Binney 98)

$$\mathrm{M_v} = 10^{12} \mathrm{M}_\odot$$ (Halo Mass, Klypin et al. 02)

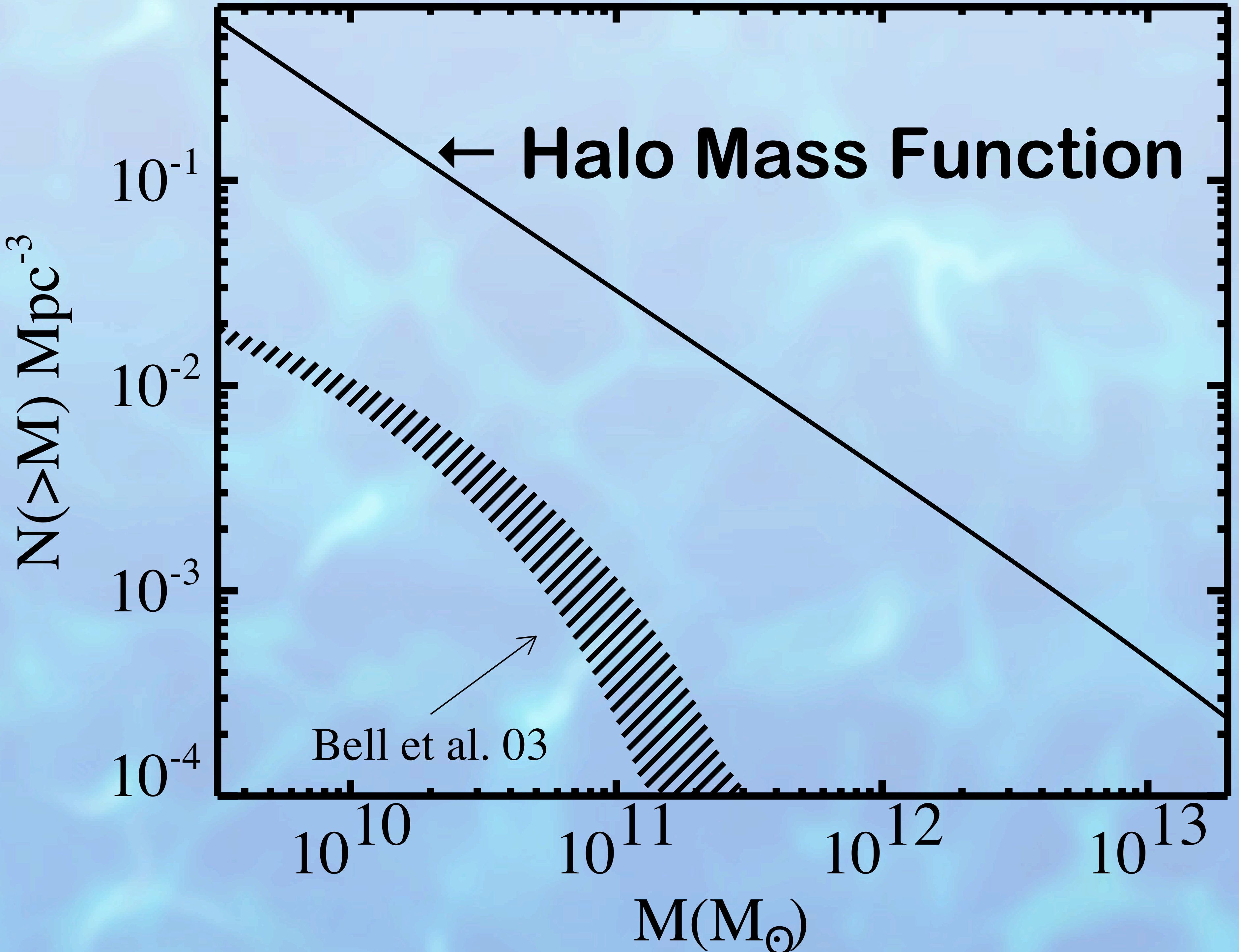
$$\mathrm{f_b} = 0.17$$ (Baryon Fraction, WMAP)

Expect ⇒ $$\mathrm{M_b} = \mathrm{f_b} \mathrm{M_v} = 1.7 \times 10^{11} \mathrm{M}_\odot$$

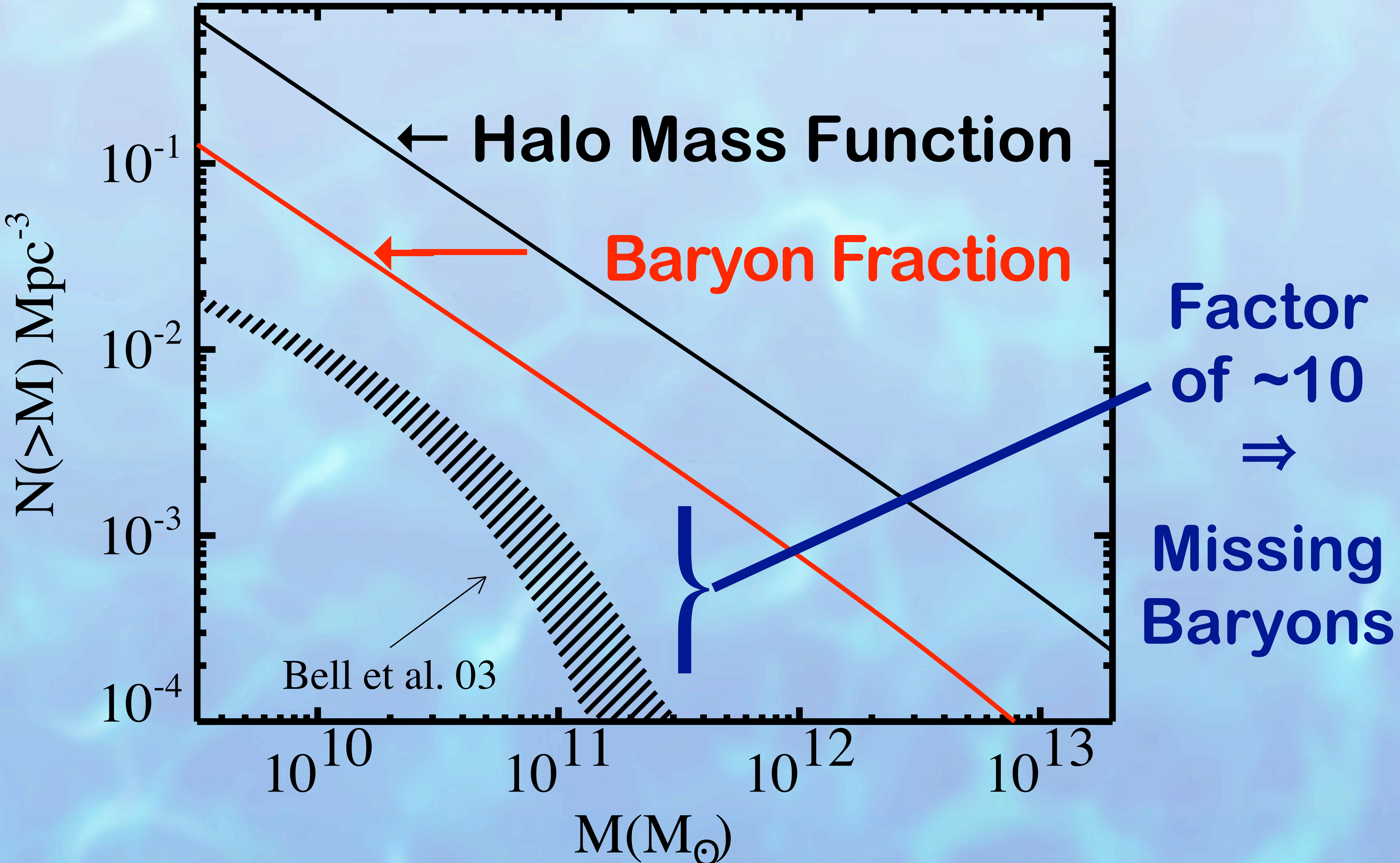
Galactic Mass Function



Galactic Mass Function



Galactic Mass Function

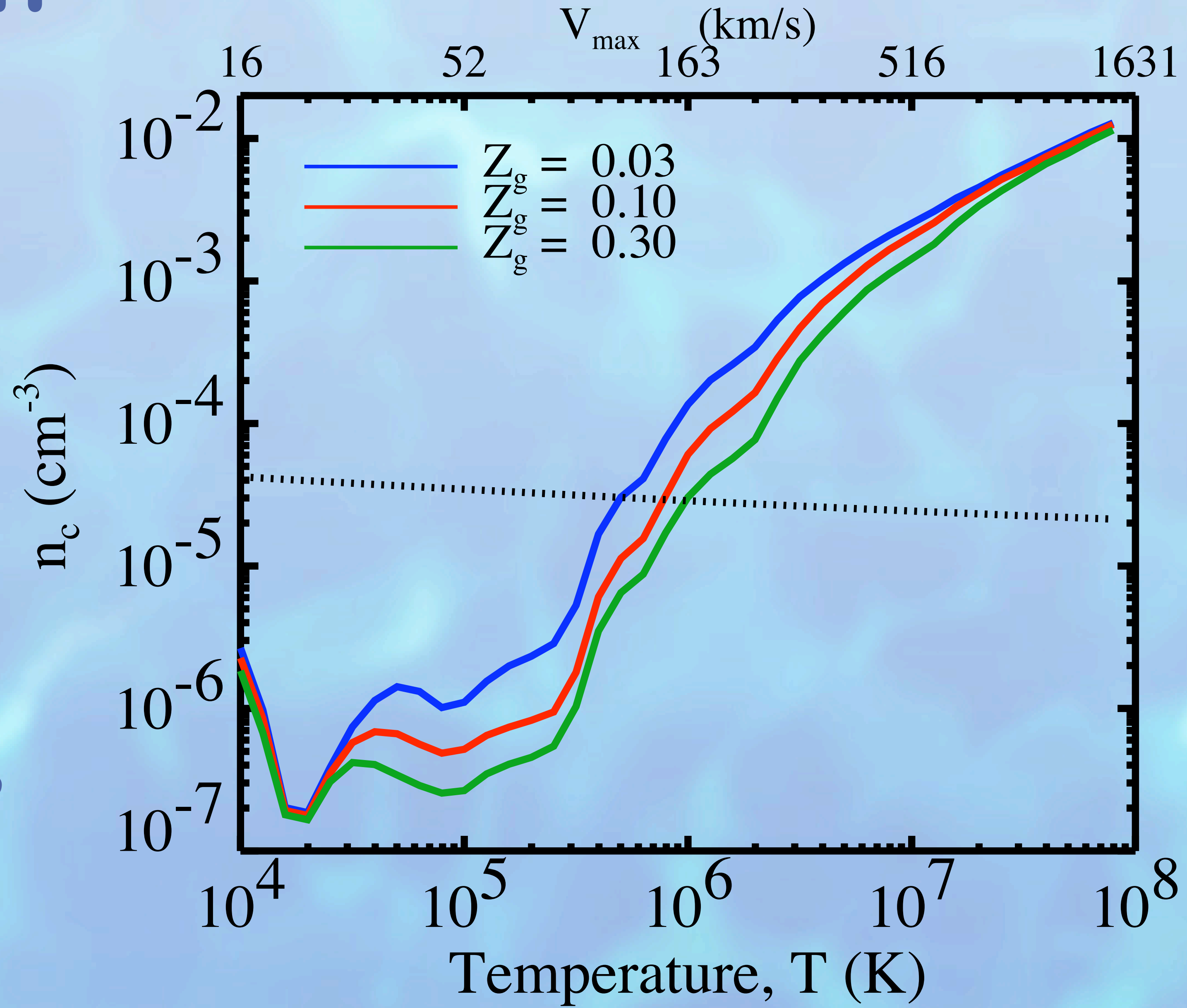


Standard Cooling

- The cooling time is:
- $$\tau_c \simeq \frac{k_b T}{n_e \Lambda(T)} \propto \frac{T^\alpha}{n_e}; \quad \alpha \sim 2$$
-
- If gas has been around longer than the cooling time, it will cool and collapse. (White & Rees 78)
- Given a halo time of formation, t_f, there is a characteristic “Cooling Density” above which gas can cool.

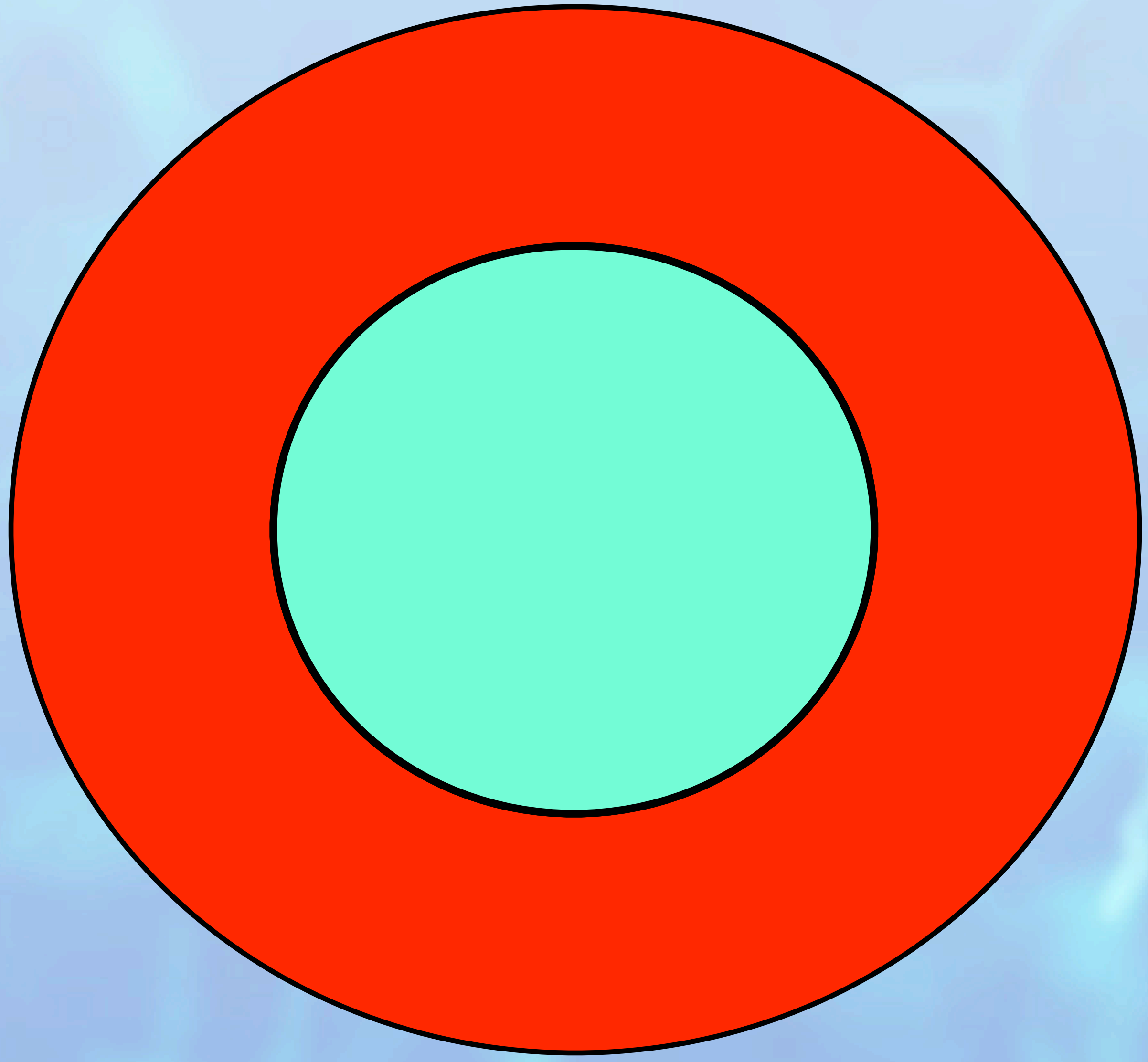
Cooling Density increases with halo mass

- Most gas cools in Galaxy halos
- Stays hot in clusters.
- "**Cooling Radius**" is set by the radius where initial hot gas density equals cooling density

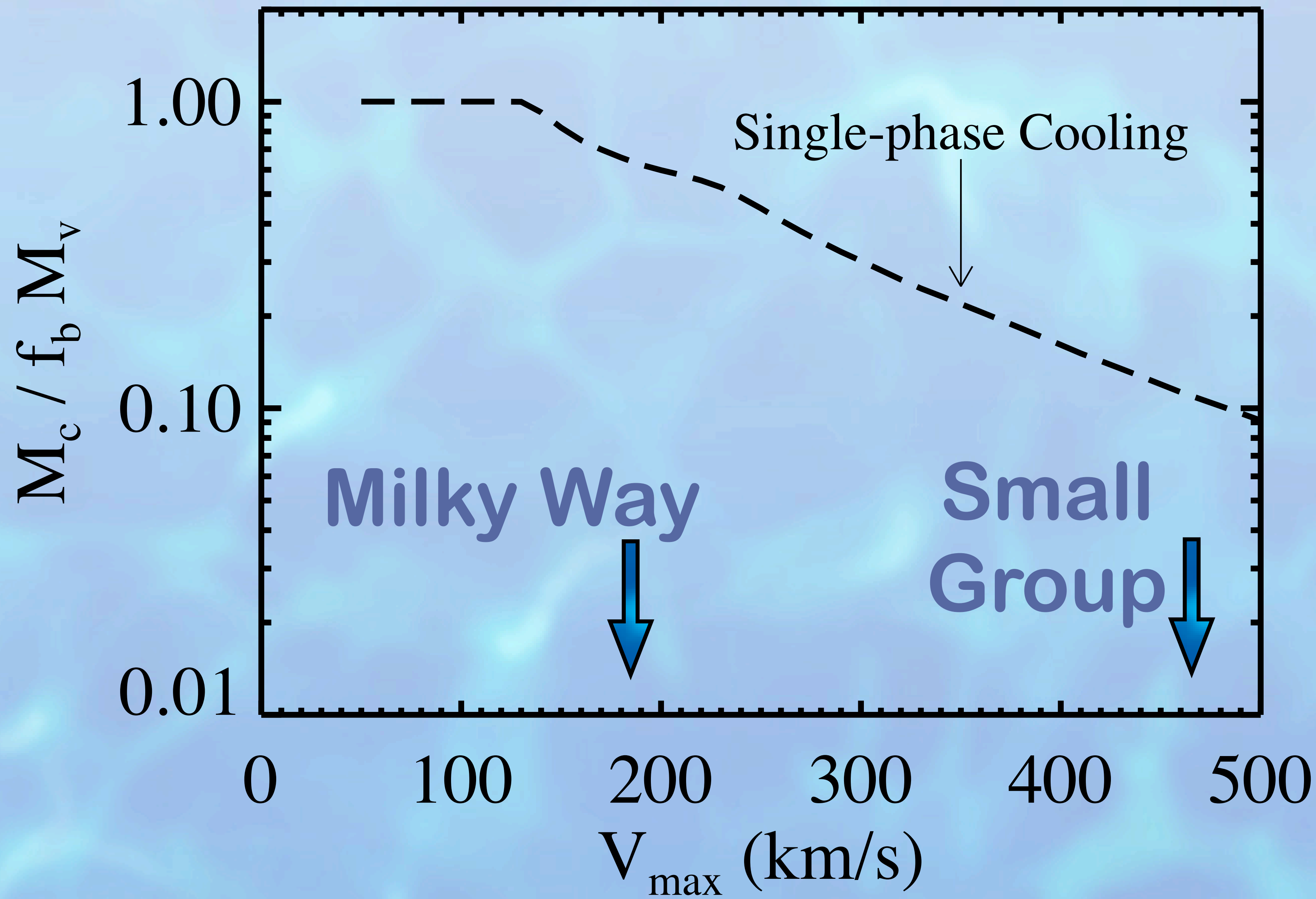


Standard Cartoon

- Halo collapses, gas shock-heats to halo temperature.
- All gas within the Cooling Radius cools together, as single phase.
- Falls in monolythically to form a central galaxy.



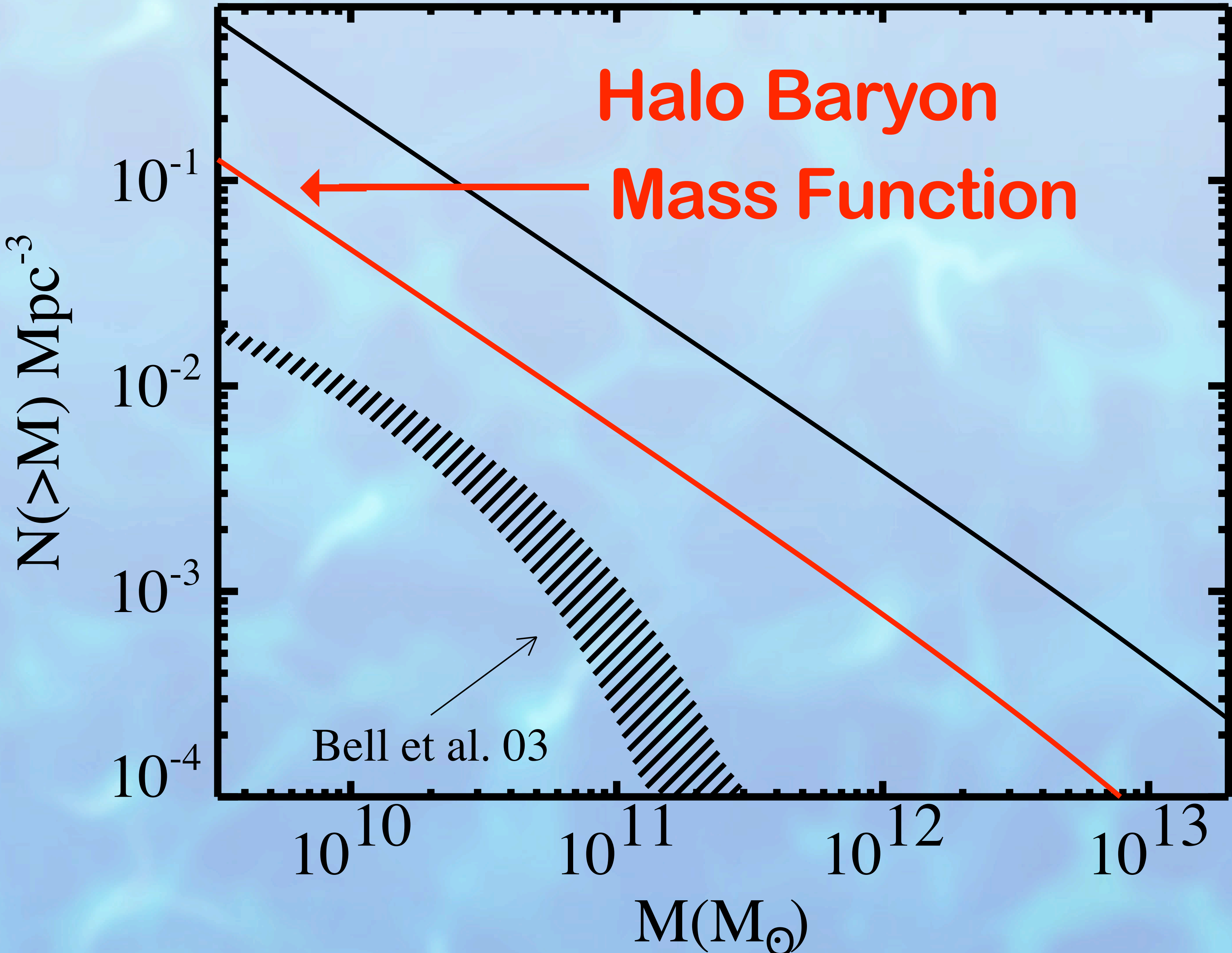
Standard Model: Fraction of baryons that cool



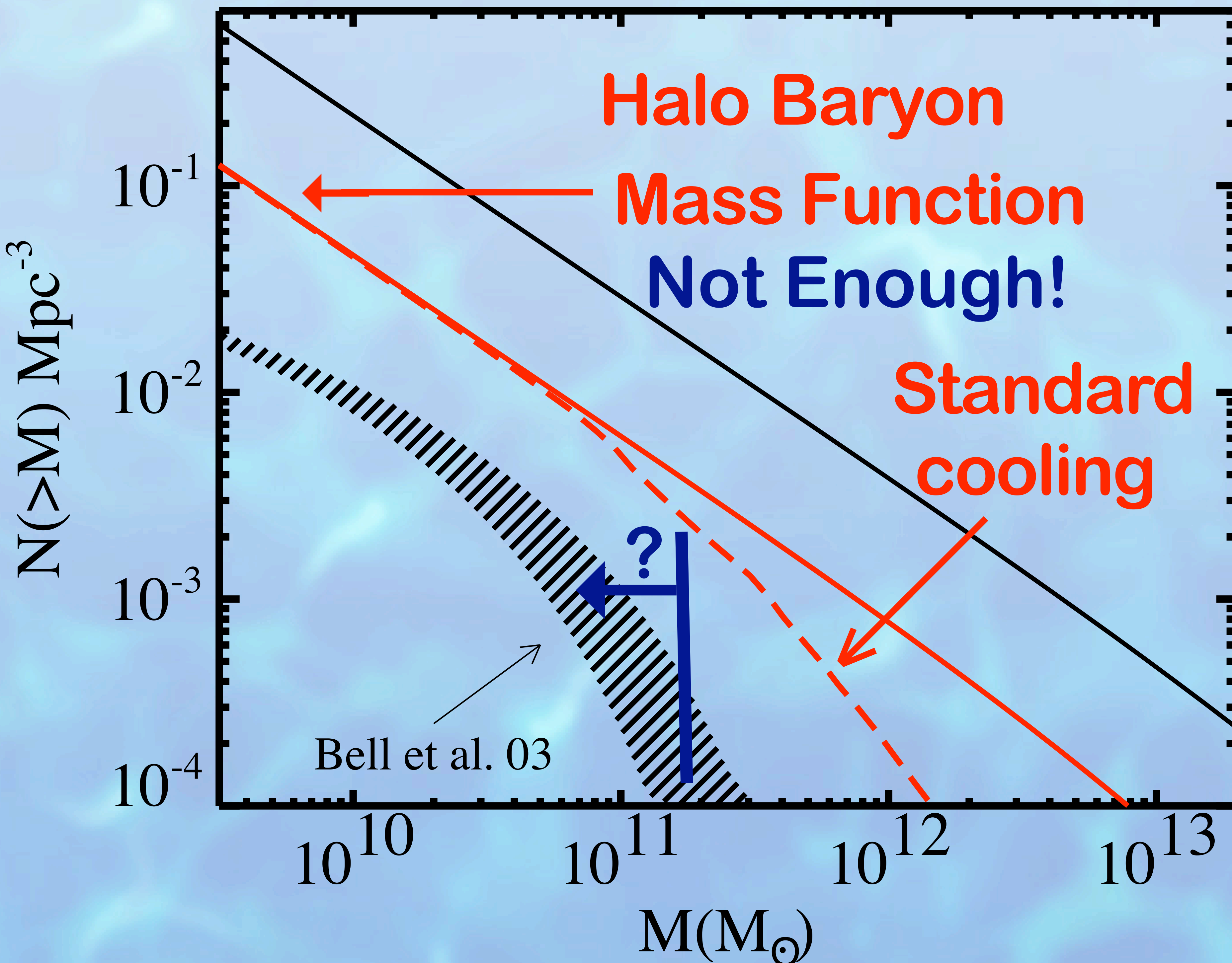
What about the Milky Way?

- Standard treatment implies that 2/3 of the Milky Way halo baryons cool. The implied disk mass would be, $12 \times 10^{10} \mathrm{M}_{\odot}$, twice what is observed.
- Typically, supernova feedback is invoked to blowout *half* of the mass that initially cooled, without destroying the thin disk!
- Energetic arguments suggest that SN feedback should only become important in low-mass halos , $\mathrm{V}_{\mathrm{max}} < 100 \mathrm{km\,s}^{-1}$, much smaller than the mass/velocity scale of the Milky Way (e.g. Dekel & Silk 86).

Galactic Mass Function



Galactic Mass Function



A New Approach

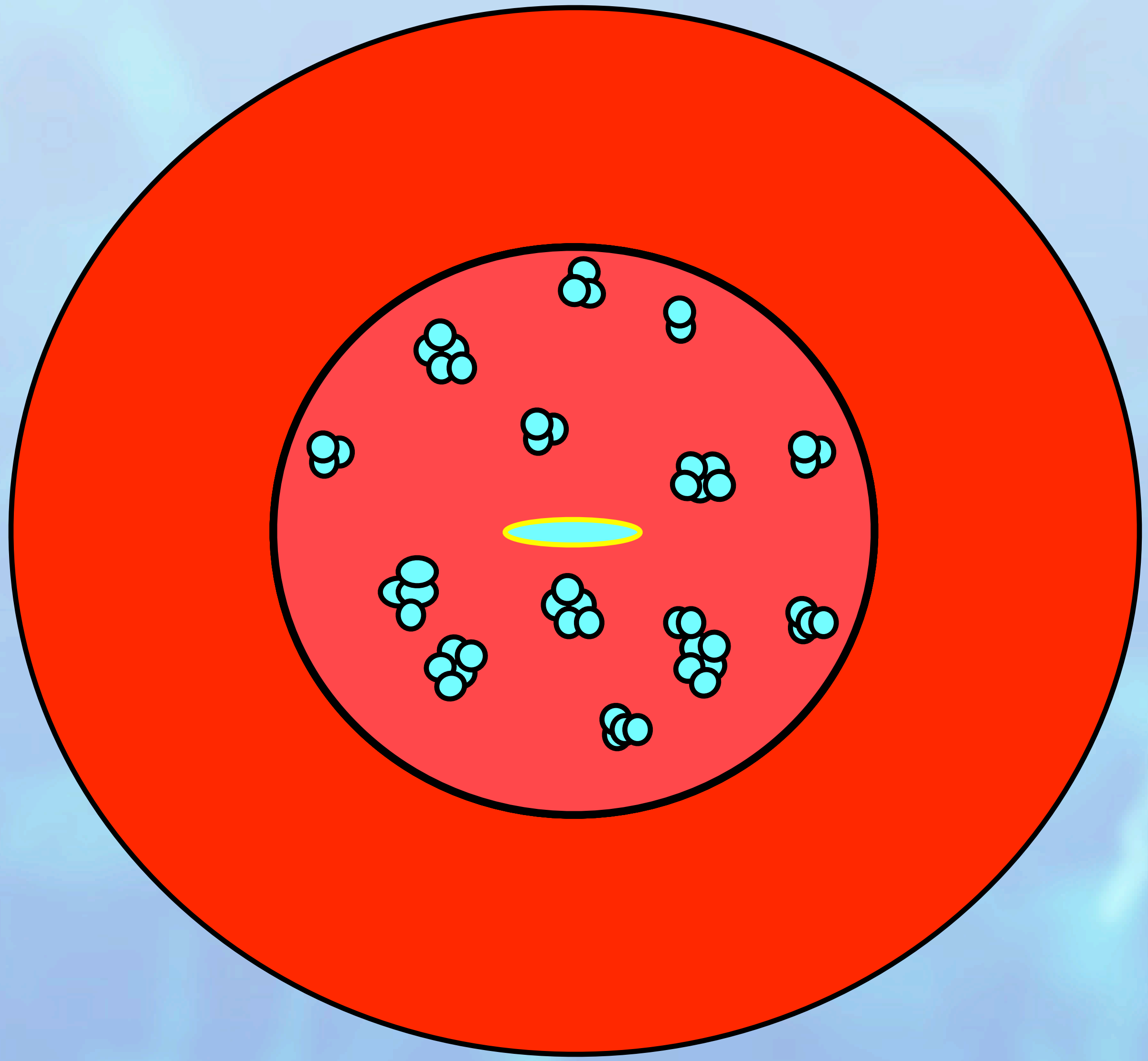
- The Thermal Instability
- Cloud Fragmentation
- A Residual Hot Core

Cooling and Fragmentation in Astrophysical Plasmas

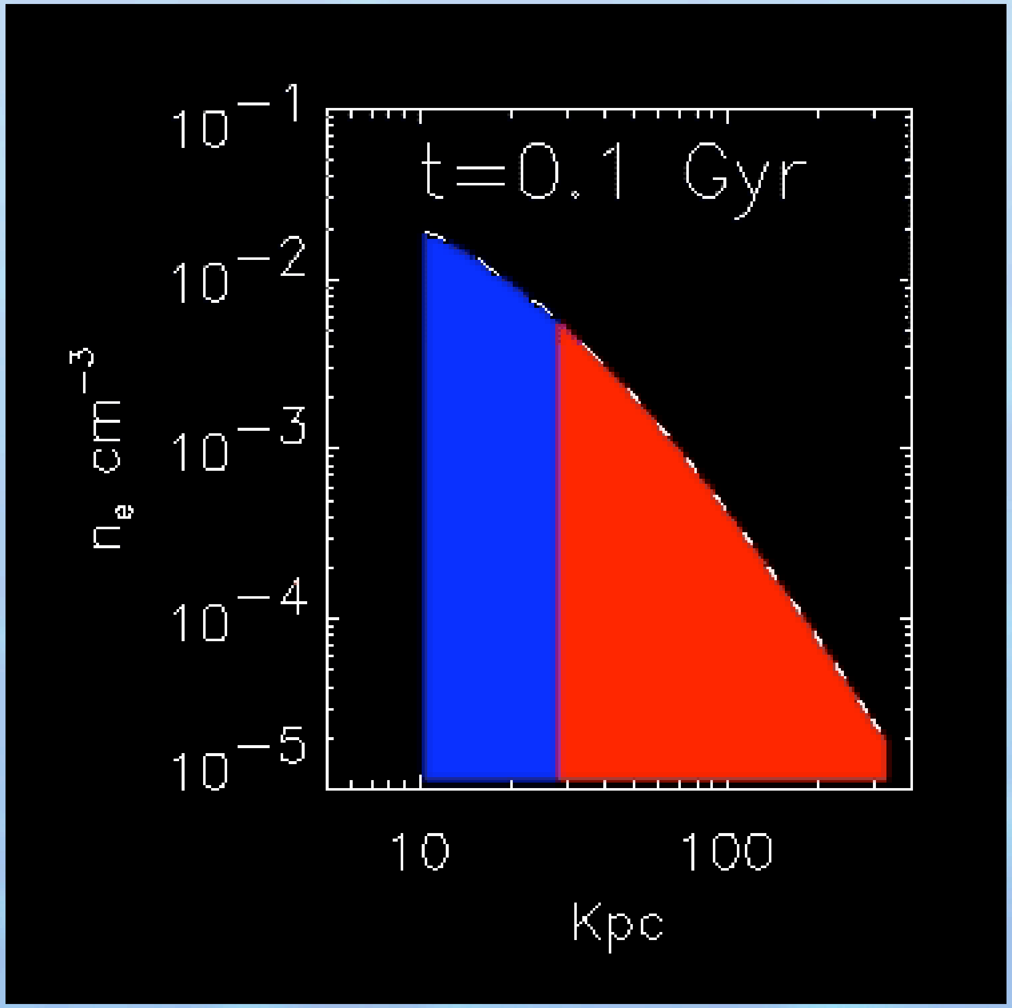
- A cooling plasma is hydrodynamically unstable (Field 1965):
-
$$\tau_c \simeq \frac{\mathbf{k_b T}}{\mathbf{n_e \Lambda(T)}} \propto \frac{\mathbf{T}^{\alpha}}{\mathbf{n_e}}; \quad \alpha > 1$$
- Inhomogeneities in the initial plasma are emphasized: Overdense regions cool more quickly & get denser as a result. Underdense regions, vice versa.
- The result is a two phase medium: A low density, hot gas surrounds a population of cooled (~ 10^4 K) clouds, pressure-supported within the hot gas background.

Fragmented Cooling

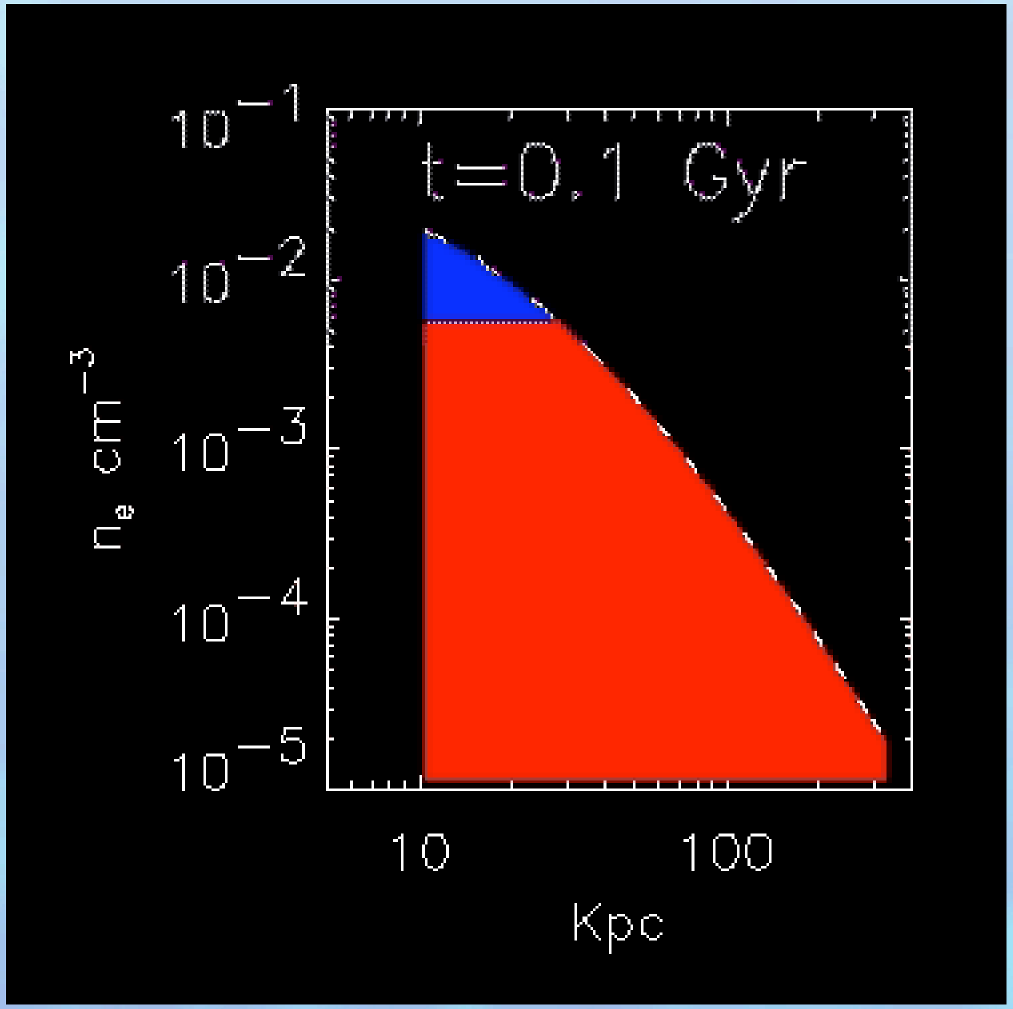
- Gas Within the Cooling Radius Fragments into Cooled Clouds + Hot Background.
- Clouds Fall in to form galaxy after dissipating energy.
- Hot Core Remains.



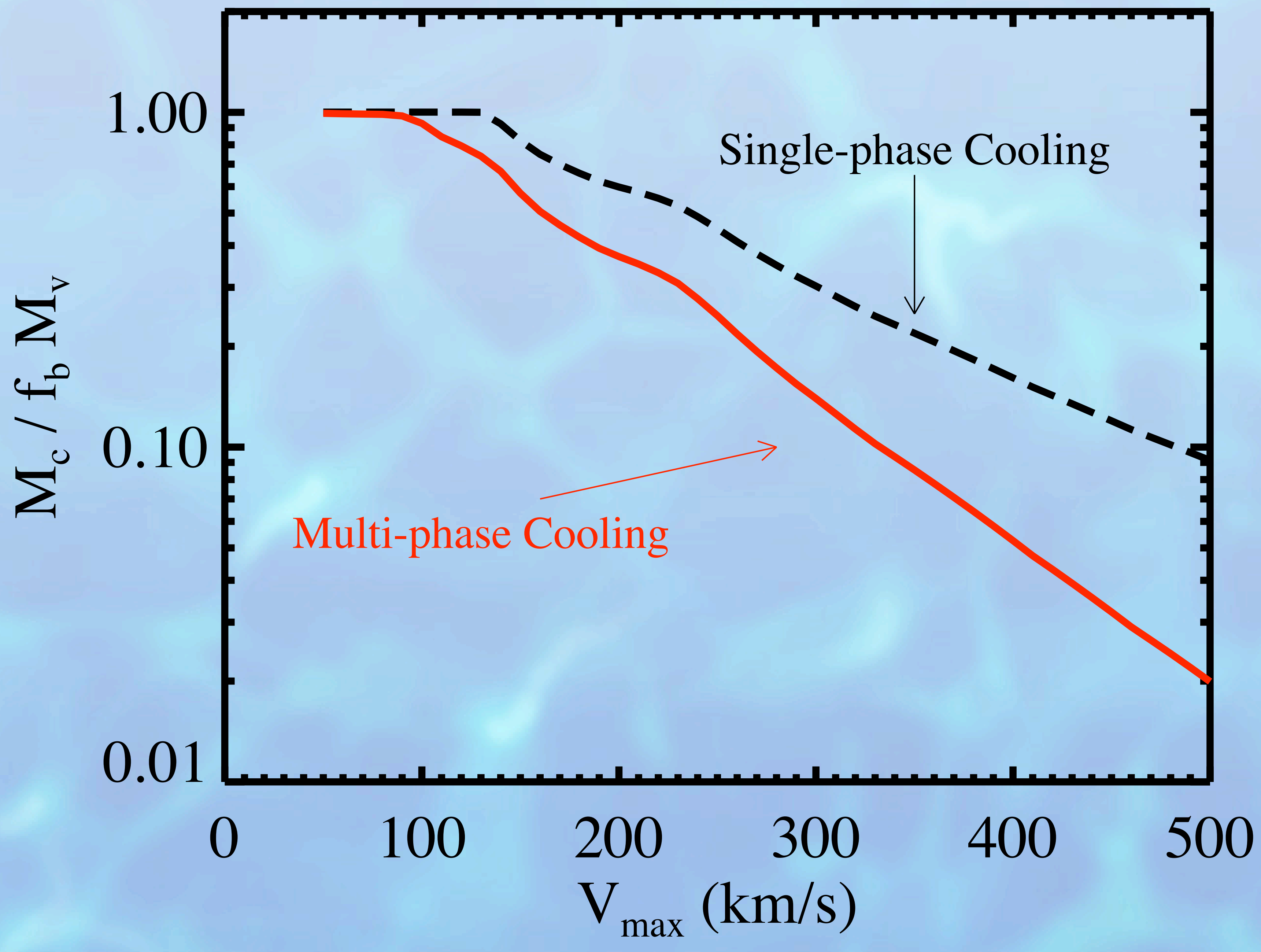
old cartoon



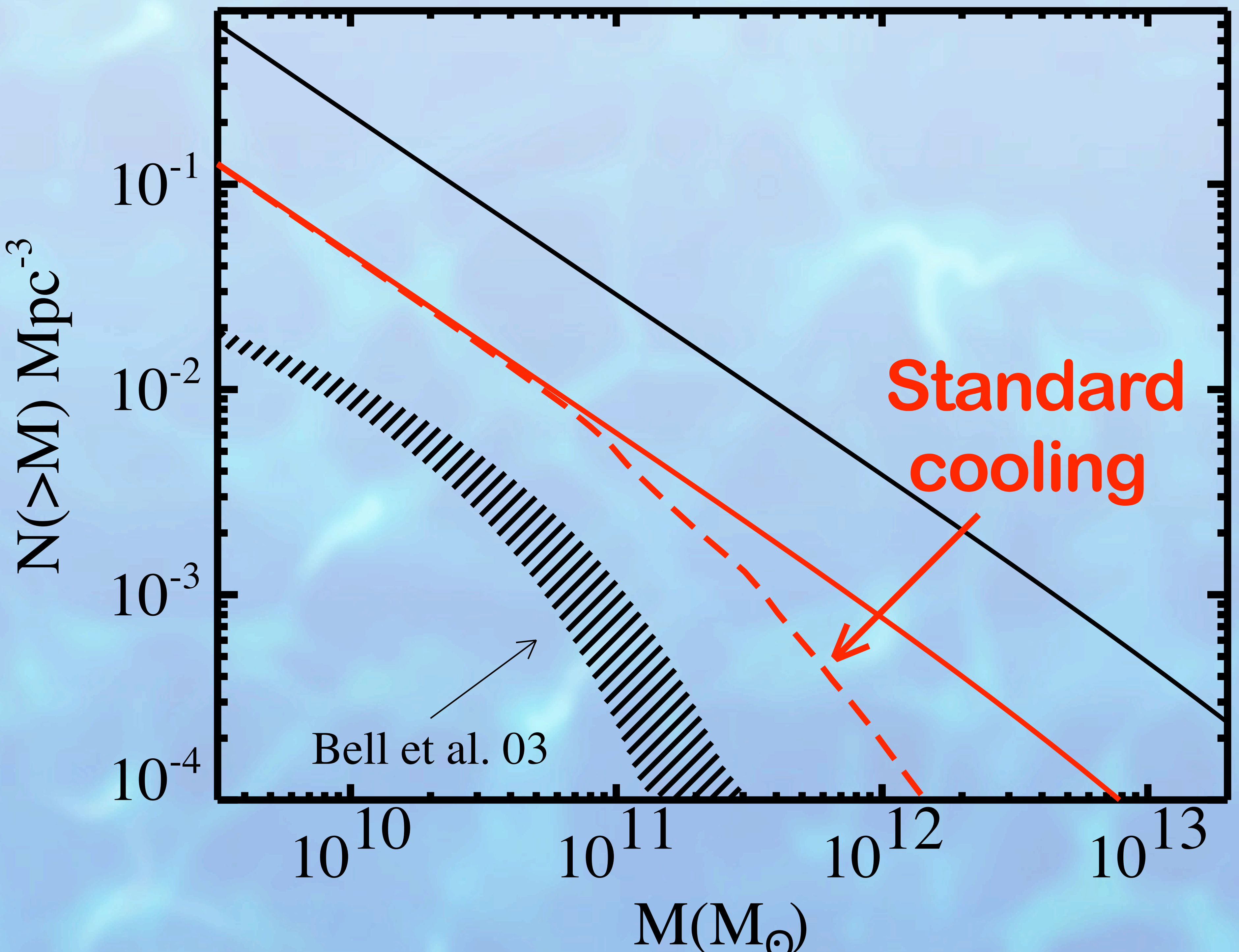
new cartoon



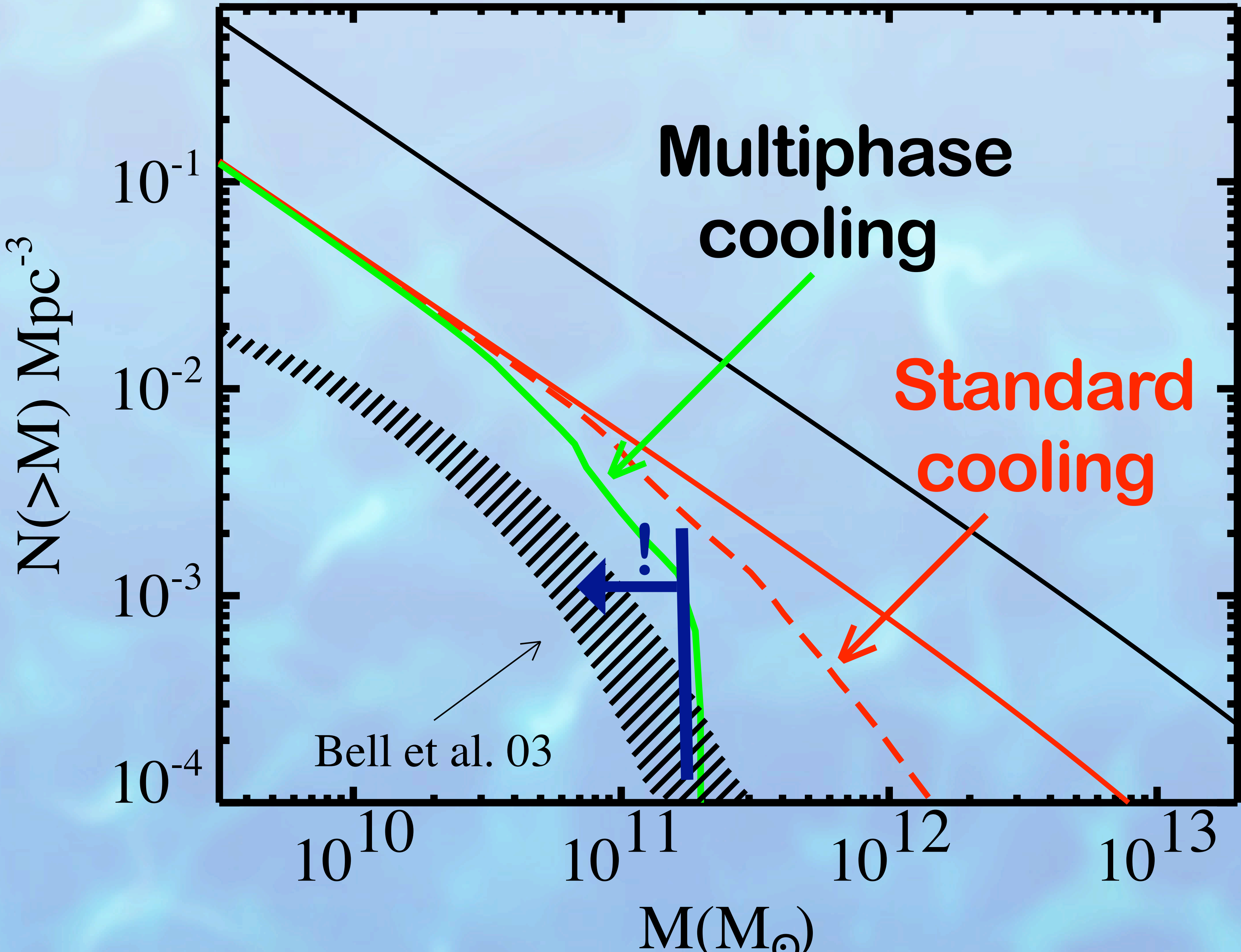
Fraction of baryons that cool



Galactic Mass Function



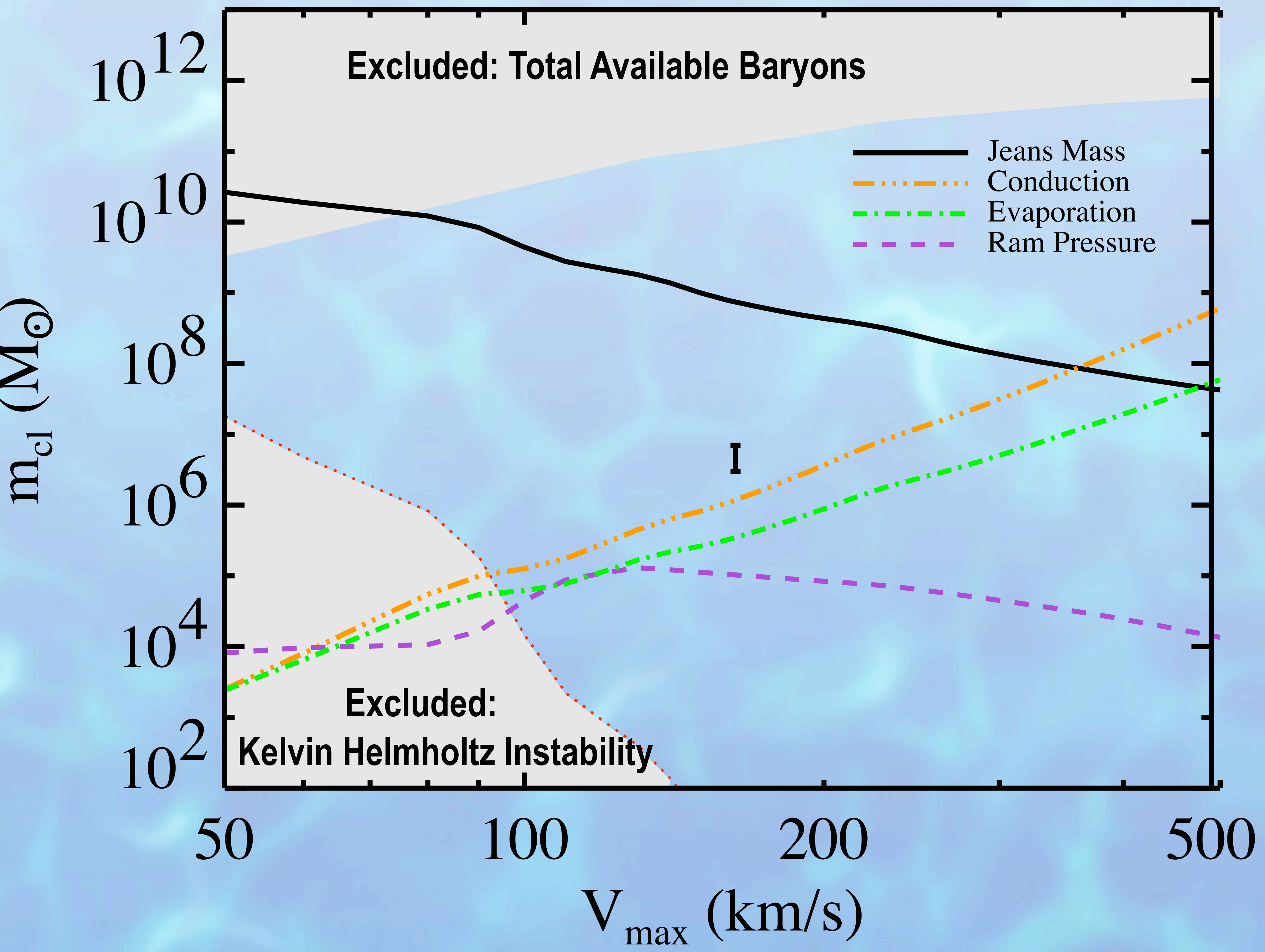
Galactic Mass Function



Cloud Properties

- Cloud densities will be set by pressure-confinement within the ambient hot-gas core:
- $$\rho_{\mathrm{cl}} \simeq \rho_{\mathrm{hot}} \frac{\mathrm{T_{hot}}}{\mathrm{T_{cl}}} \simeq 100\rho_{\mathrm{hot}}$$
- Characteristic cloud radius is therefore:
- $$\mathrm{r_{cl}} \simeq 1\mathrm{kpc} \left(\frac{\mathrm{m_{cl}}}{10^6 \mathrm{M_\odot}} \right)^{1/3} \left(\frac{\mathrm{T}}{10^6 \mathrm{K}} \right)^{-1}$$
- Cloud infall fuels galaxy formation.
- We expect some fraction of the fragmented clouds to survive as a fast-moving population in the halo

Constraints on the Cloud Mass

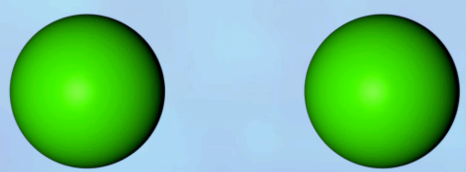


Cloud collisions & infall

- Clouds obtain velocities characteristic of halo. Fall in to fuel galaxy only after dissipating energy: $\tau_{\mathbf{infall}} \sim \mathbf{3Gyr}$

- **cloud-cloud collision** timescale

- $$\tau_{\mathbf{coll}} \simeq (\phi_{\mathbf{cl}} \mathbf{v}_{\mathbf{cl}} \mathbf{r}_{\mathbf{cl}}^{\mathbf{2}})^{-\mathbf{1}}$$



- **ram pressure drag** infall time

$$\tau_{\mathbf{ram}} \simeq \frac{\mathbf{m}_{\mathbf{cl}}}{\rho_{\mathbf{hot}} \mathbf{r}_{\mathbf{cl}}^{\mathbf{2}} \mathbf{v}_{\mathbf{cl}}}$$

Building the Galaxy...

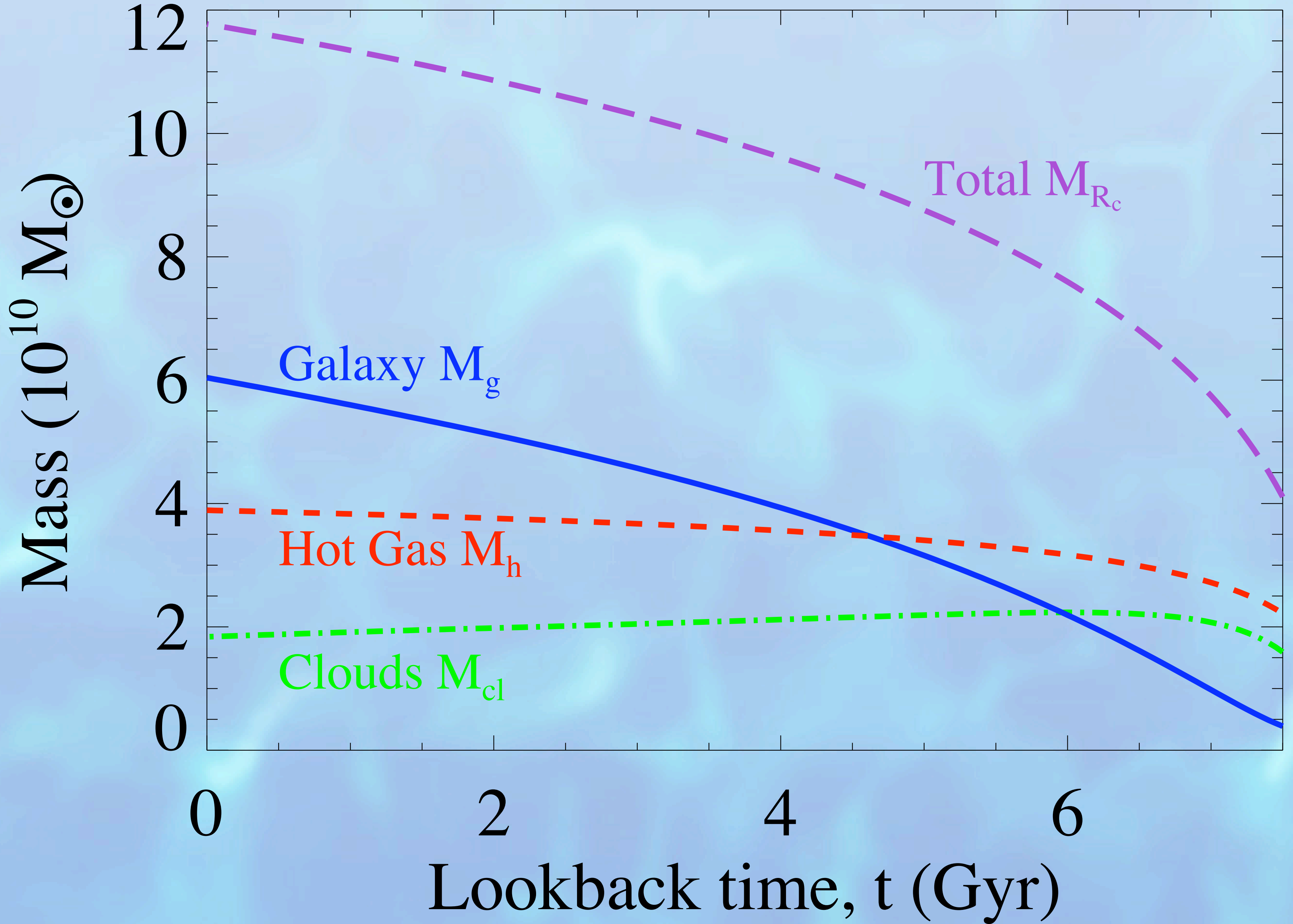
$\mathbf{m_{cl} = 5 \times 10^6 M_\odot}$

Milky Way Baryons:

50% Disk

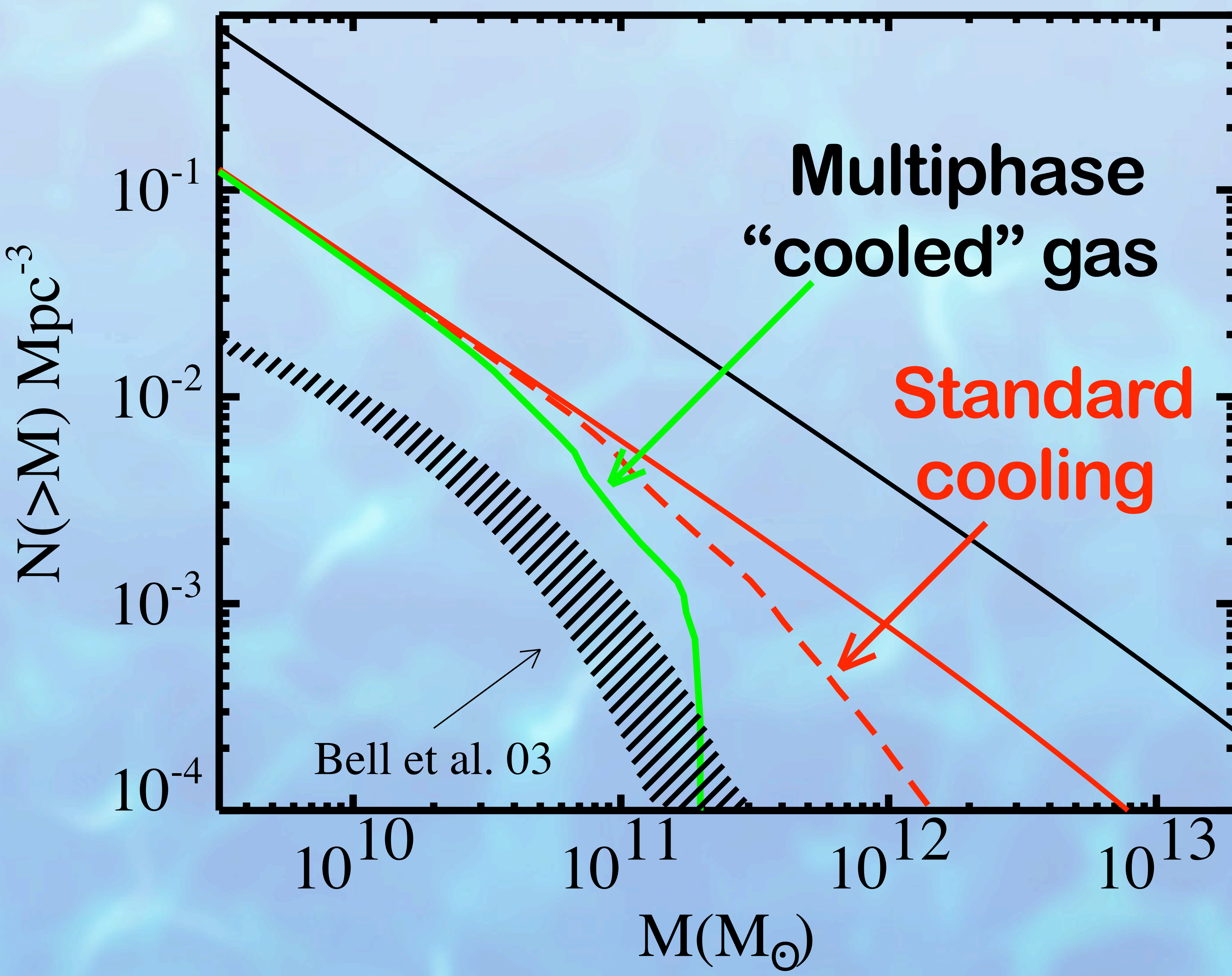
30% Hot Core

20% Clouds

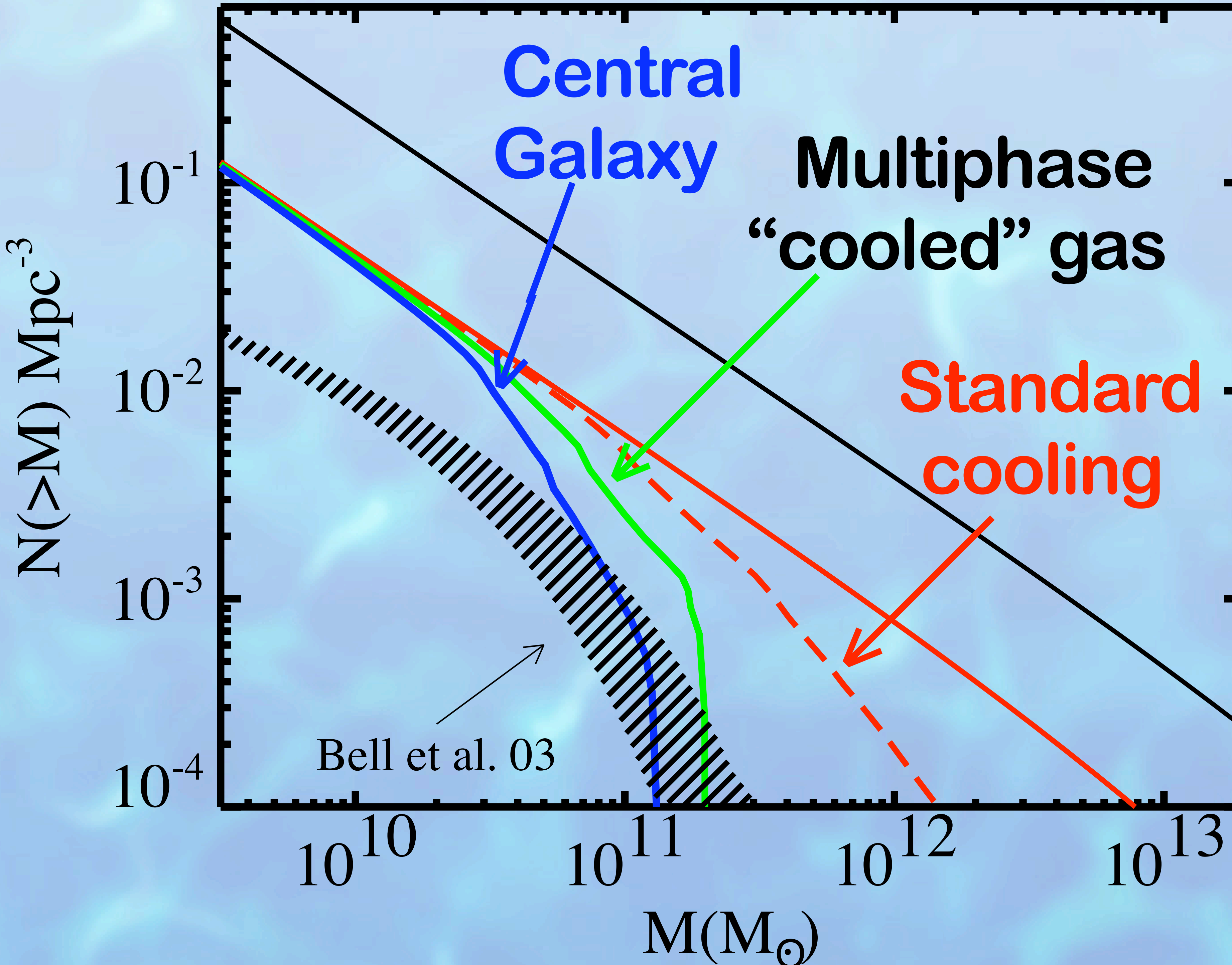


Milky Way Mass Accounted For With: $\mathbf{m_{cl} = 10^6 - 10^8 M_\odot}$

Galactic Mass Function



Galactic Mass Function

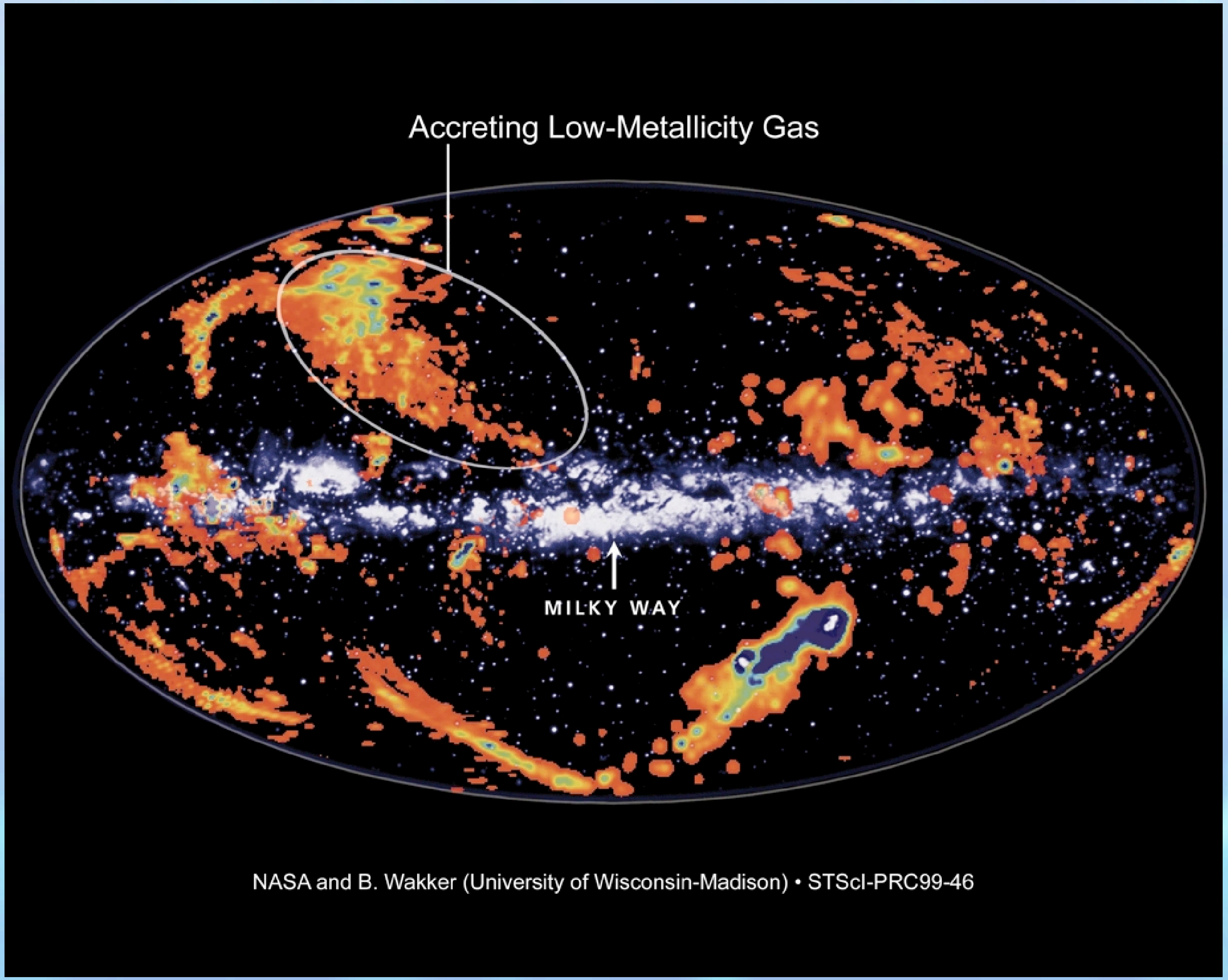


Other Reasons to Believe...

- High-Velocity Clouds
- Evidence for a Galactic Hot Gas Corona
- QSO Absorption Systems

High-Velocity Clouds

- HI clouds with velocities inconsistent with Galactic rotation
- Origin debated because of their unknown radial distances.
- Line widths FWHM: ~27km/s
- We propose that these clouds are “circumgalactic” with radii, ~100 kpc.

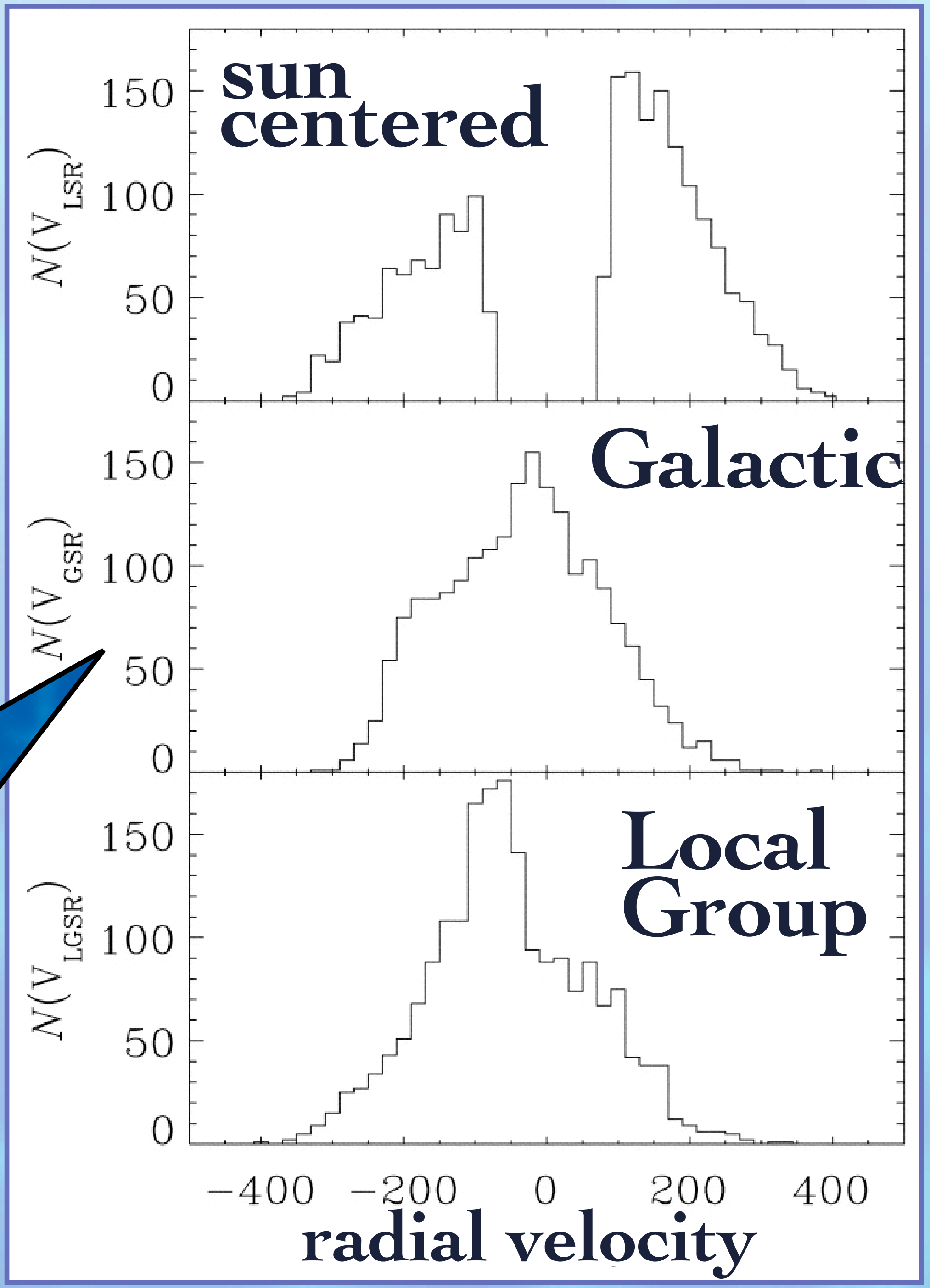


HI Survey Results

Putman et al. 02

- ~2000 HVCs over southern sky
- Angular Sizes:
- $\theta \sim 0.5\mathrm{deg}^2$
- HI Column Densities:
- $\mathrm{N_{HI}} \sim 10^{19}\mathrm{cm}^{-2}$
- Velocity dispersion of population narrowest in Galactic Standard of Rest:

$$\sigma_{\mathrm{r}} \simeq 115\,\mathrm{km\,s^{-1}}$$

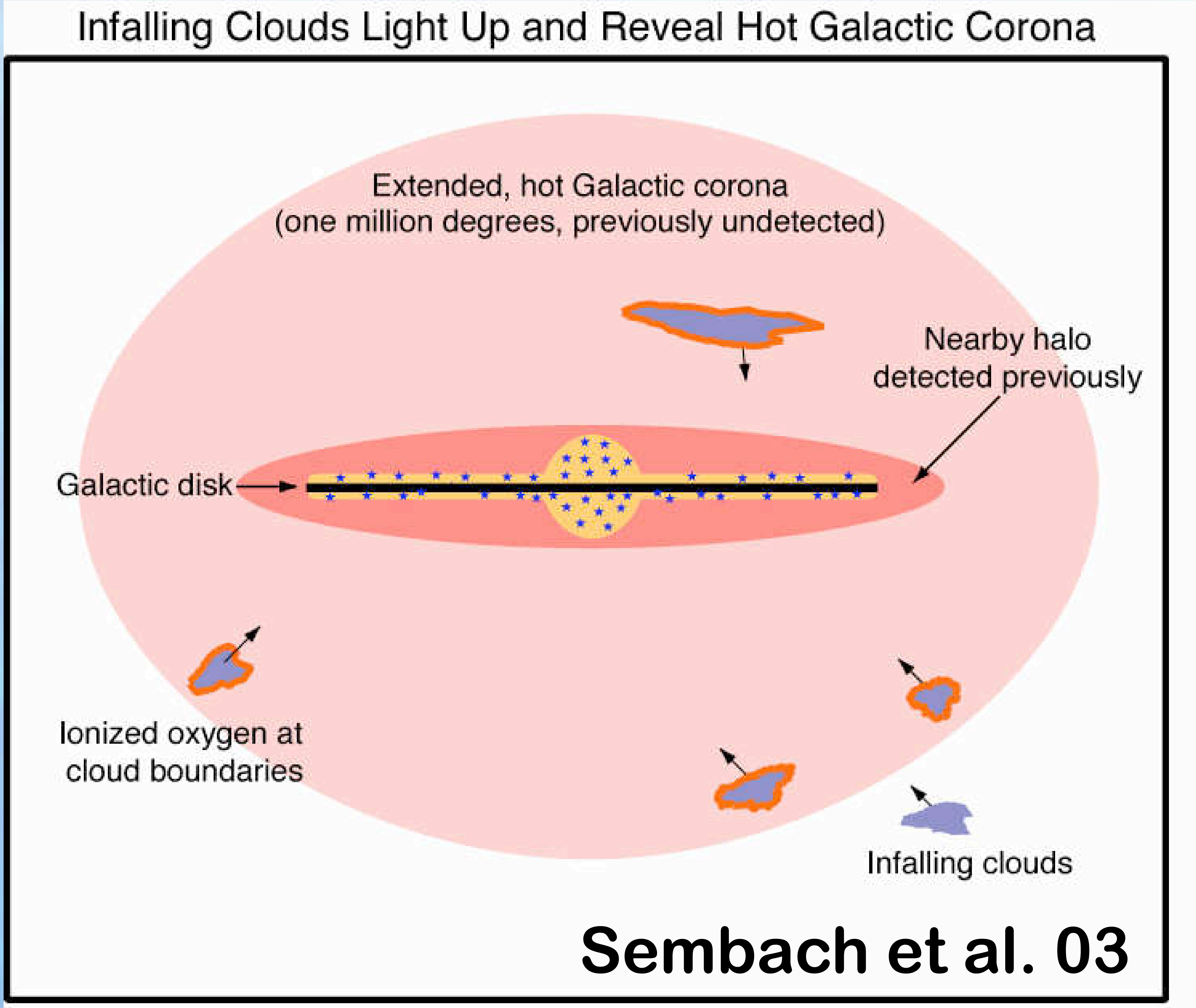


Model Expectations

- 10^4 K clouds ⇒ FWHM = 25 km/s
- Clouds obtain halo velocity dispersion
  $\Rightarrow \sigma_r \simeq 115\,\mathrm{km\,s^{-1}}$
- Clouds of mass $m_{cl} = 5 \times 10^6 M_\odot$ imply:
  - $\theta \simeq 0.5\mathrm{deg}^2$
  - $N_{HI} \simeq 1.5 \times 10^{19}\mathrm{cm}^{-2}$
  - $M_{cl} = 2 \times 10^{10} M_\odot$ (shown earlier)

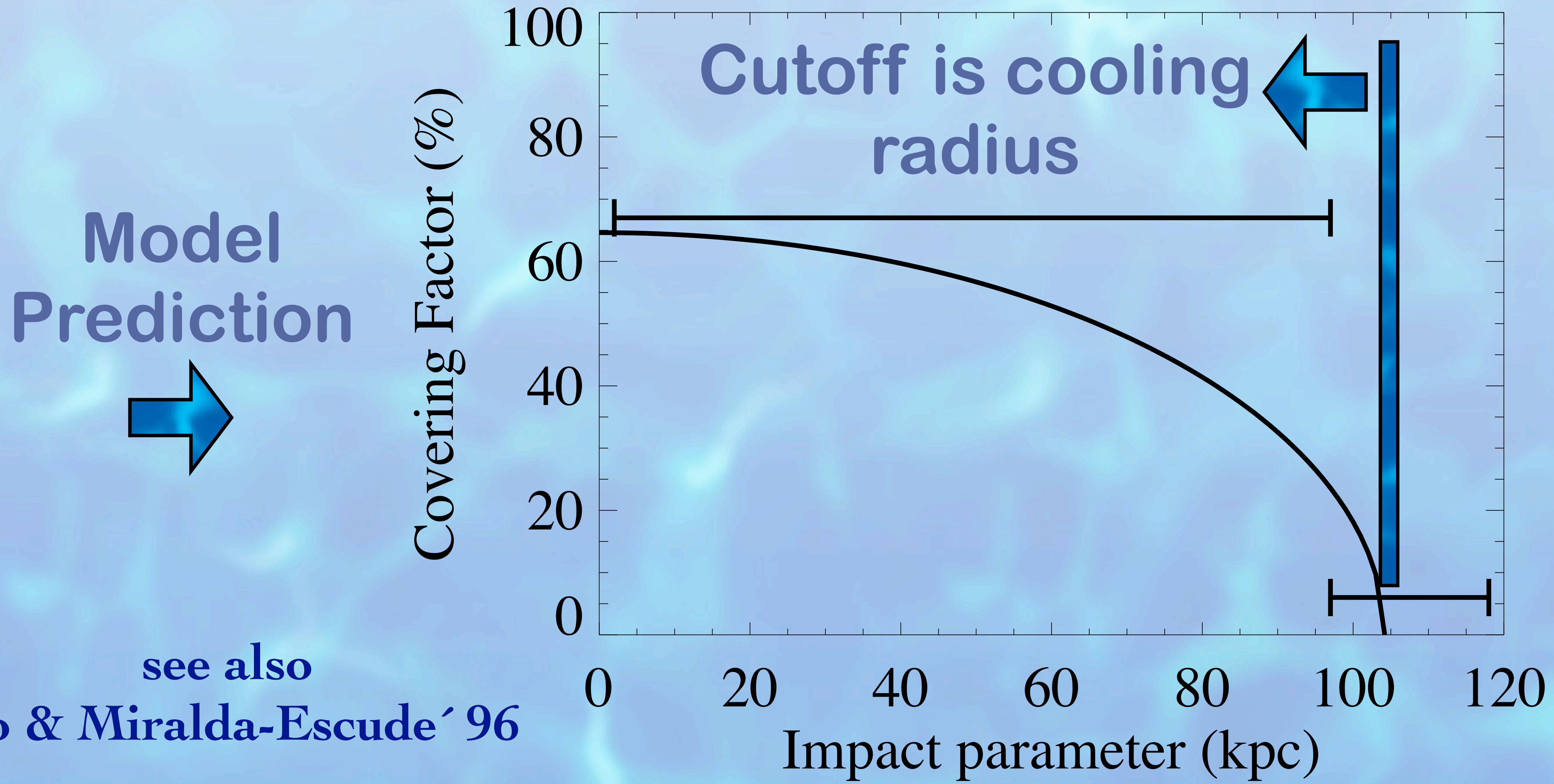
  or $N_{cl} = 2000$ in the southern sky

FUSE study of OVI absorption in Galactic Halo



Quasar Absorption Systems

- Warm gas is seen around other galaxies as quasar absorption systems. e.g., CVI-absorbing gas is highly ionized, low-density
- Chen et al. (2001) found that 68% of galaxies show CIV absorption within 100 kpc of their centers, while only 6% show any CIV absorption beyond 100kpc.



see also
Mo & Miralda-Escude´ 96

Conclusions

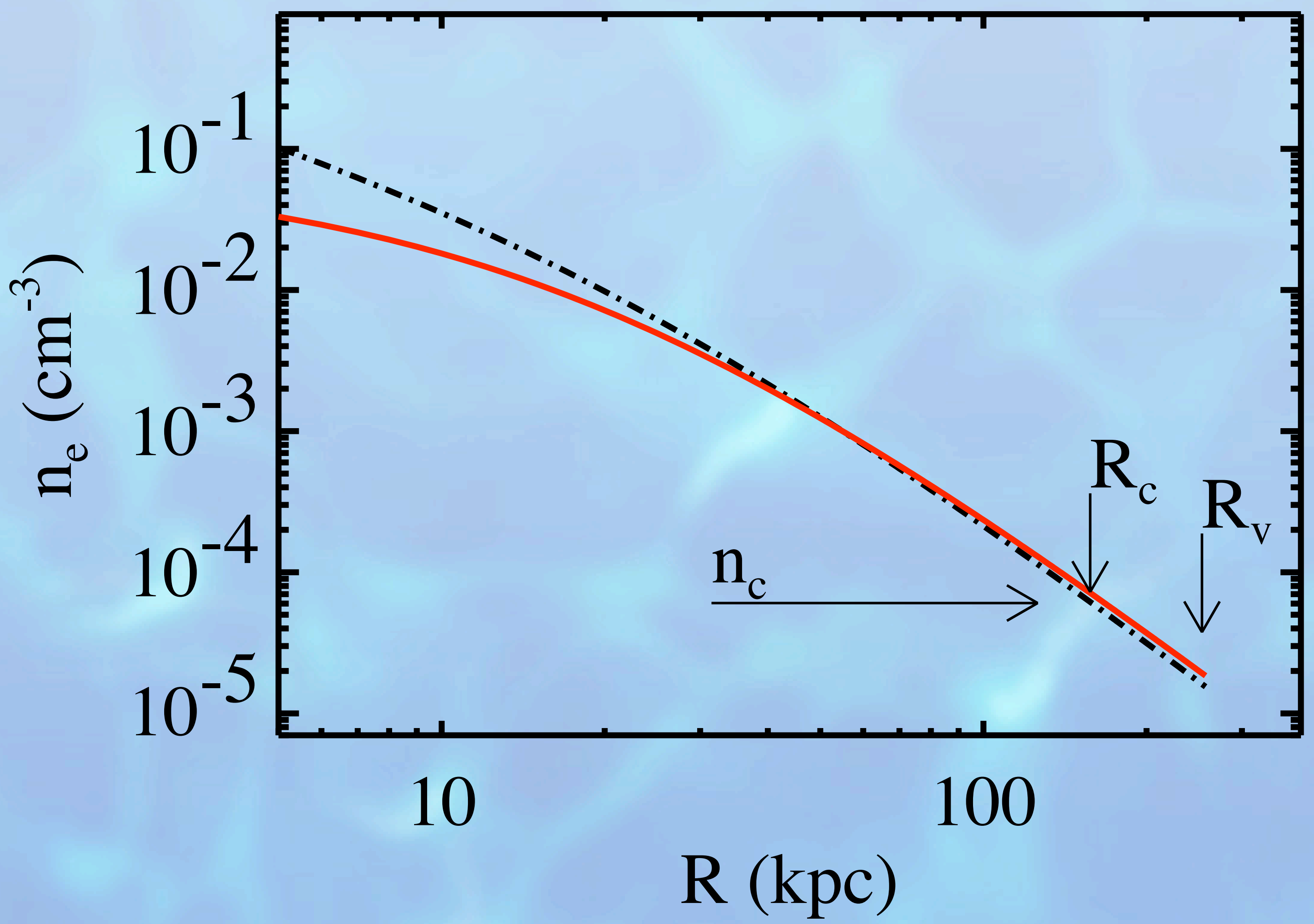
- The Thermal Instability Leads to Fragmented Gas Cooling
- Galaxy formation is fueled via infall of warm clouds, pressure-supported in hot-gas ambient background
- Naturally gives rise an upper limit on central, quiescent galaxy masses of $\sim 10^{11}$ M_o
- Explains the characteristic mass of galaxies & exponential cutoff in galaxy luminosity function without feedback.
-

Conclusions

- Clouds of mass $(3-7)\times10^6\mathrm{M}_\odot$ explain high-velocity clouds as a “circum-galactic” population at ~100 kpc
  - Reproduce: HVC sizes, column densities, line widths, and velocity distribution.
- Clouds of the same mass help explain the mass of the Milky Way without extreme feedback
  - Halo Baryons: 50% Galaxy, 30% Hot Core, 20% Clouds.
- Explain QSO absorption system trends

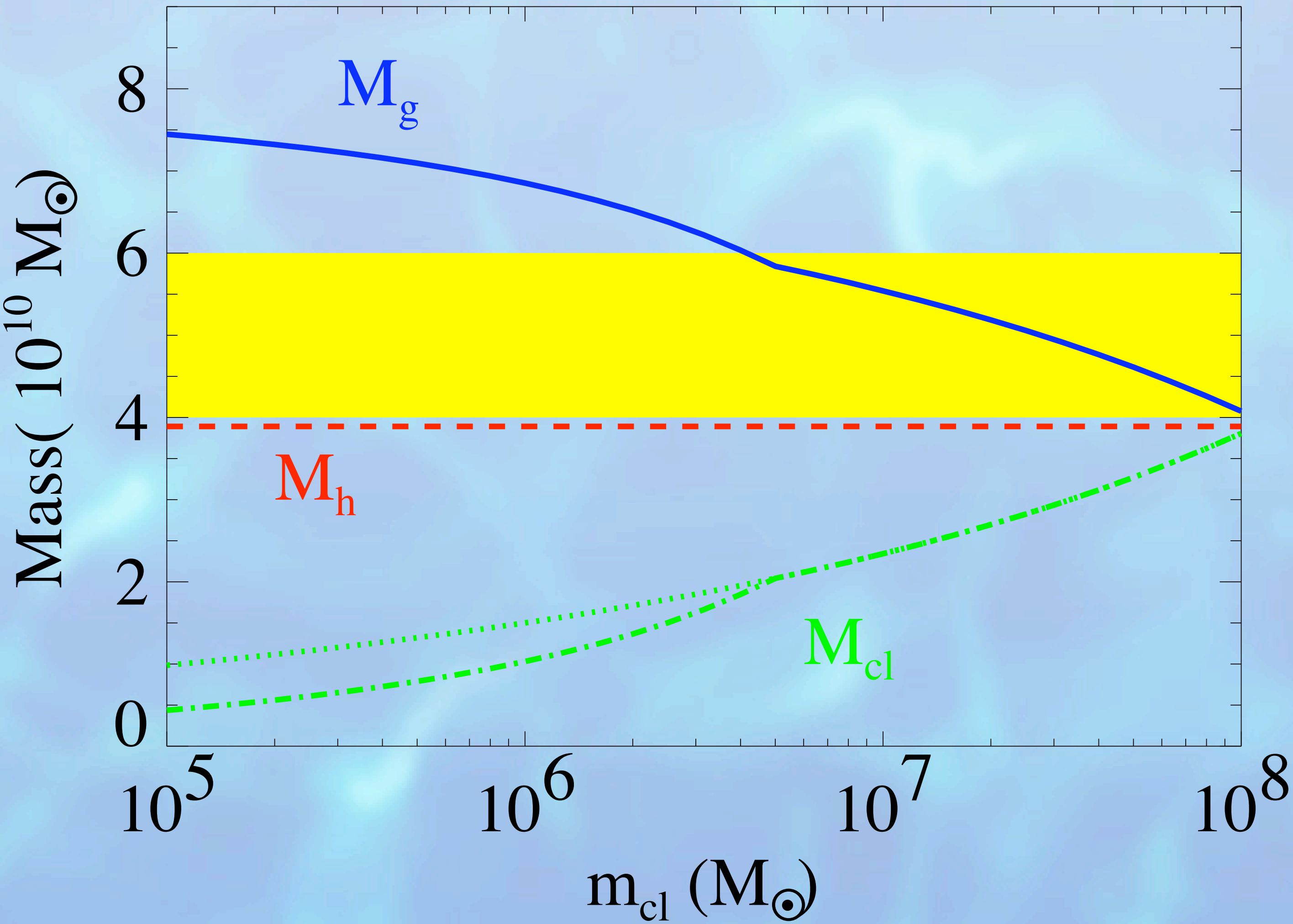
Thanks.

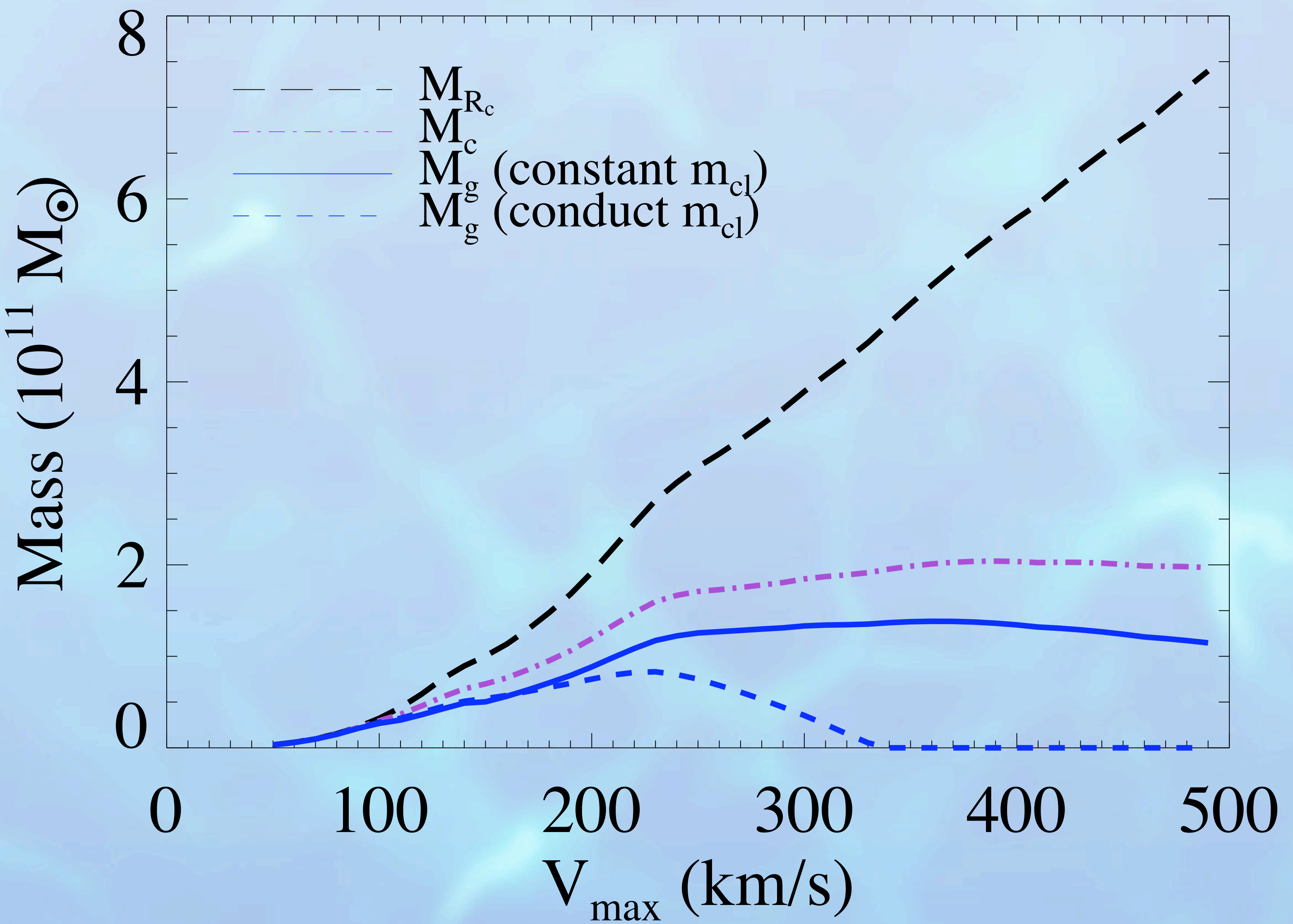
Cooling Density sets a "cooling radius" for each halo



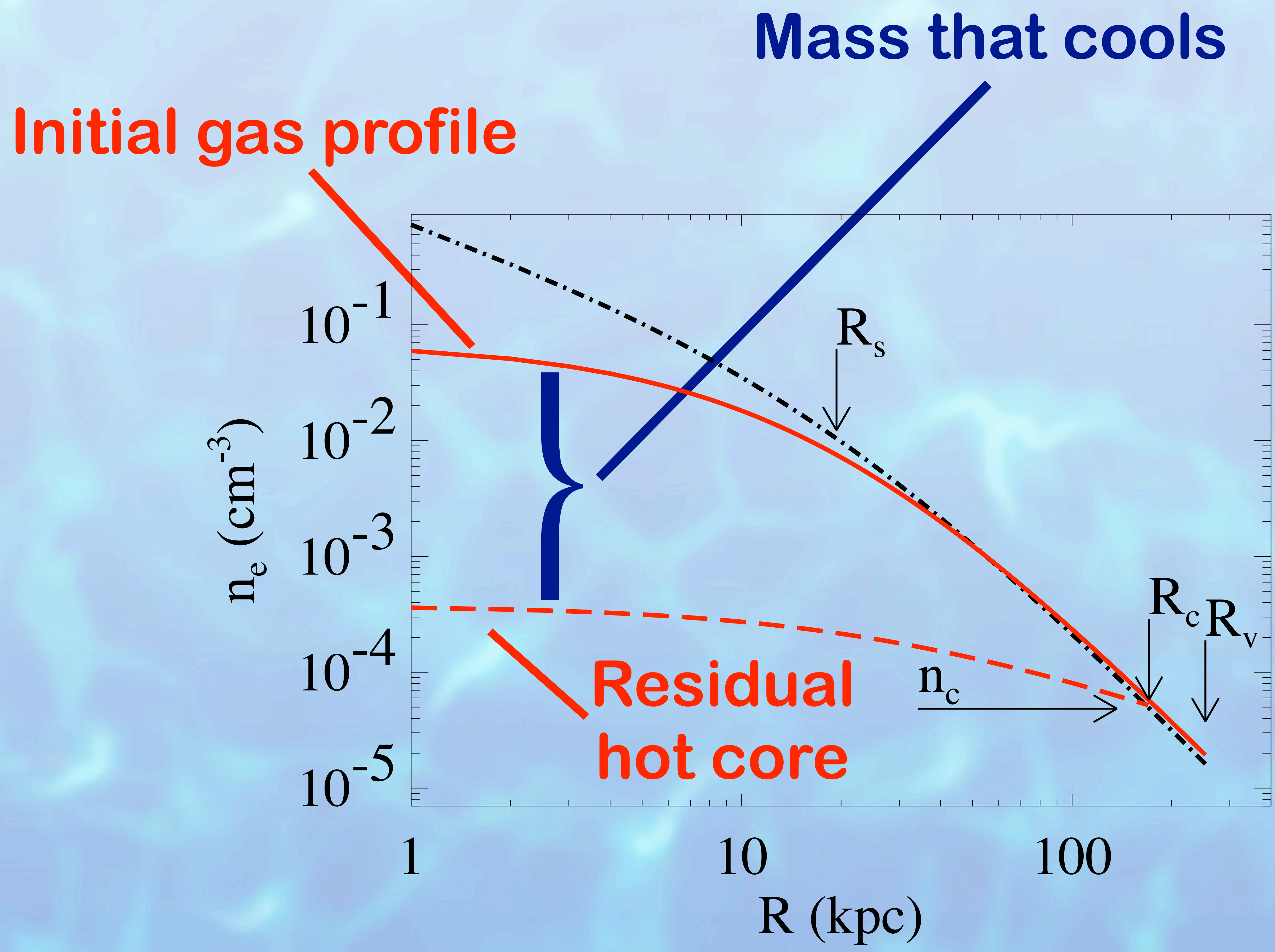
- White&Frenk 91
- All gas inside cooling radius cools, forms galaxy

Mass of the Milky Way

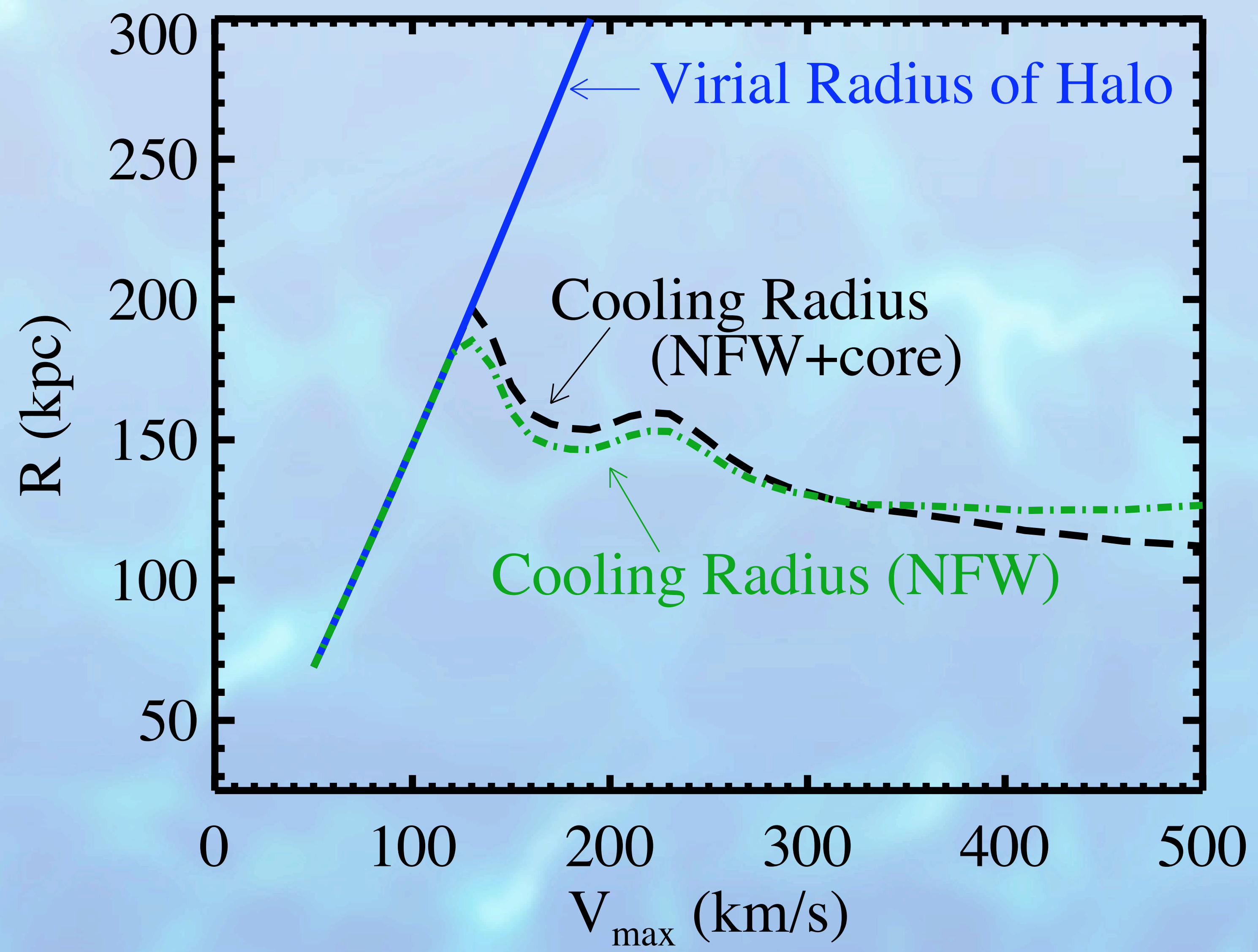




$M_h \propto \rho_c R_c^3 \propto V_{\max}$ $\quad$ $M_{dm}(R_c) \propto V_{\max}$



Mass that cools
Initial gas profile
Residual
hot core
R_s
R_c
R_v
n_c
n_e (cm^{-3})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
10
100
R (kpc)


300
250
200
150
100
50
0
100
200
300
400
500
R (kpc)
V_{max} (km/s)
Virial Radius of Halo
Cooling Radius
(NFW+core)
Cooling Radius (NFW)